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The modelling and simulation of bipolar hybrid stepping motor by Matlab/Simulink

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Abstract

Development of digital electronics and microcontroller systems has led to development of electrical motors capable to tee digitally controlled. These motors are widely known as stepper motors and the enable transformation of pulsed electrical excitation into mechanical energy.
Matlab/Simulink is used as a simulation tool for bipolar stepper motor enabling motor transient characteristics of current, voltage, torque and speed to be obtained. Different operating motor regimes are simulated as no-load and rated load operation. Te obtained results are in good accordance with the theoretical expectation and with the results of analytical computations. Adequate conclusions regarding motor performance characteristics are derived.

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Keywords: modeling; simulation; model; hybrid stepper motor; simulink; motor's operating regime.

1. Introduction

The stepper motor is an electromechanical actuator which converts the input pulse train into a precisely defined increment in the shaft position. Each pulse moves the shaft through a fixed angle, called step angle. Stepper motors have emerged as cost-effective alternatives for DC servomotors in high-speed, motion control applications, where the high torque is not required, with the improvements in permanent magnets and the incorporation of solid-state

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circuitry and logic devices in their drive systems. These motors are commonly used in measurement and control applications, such as positioning systems for NC machines, ink jet printers, robotics, computer peripherals, automotive devices and small business machines[1, 2]. Although stepper motor are known for a long time, they have achieved their wide popularity in the last thirty years due to development of electronics which enables construction of cheap and reliable control circuits capable to satisfy complex requirements regarding motor torque, speed and angular displacement. In order their transient performance characteristic to be analyzed Matlab/Simulink [19] is chosen as simulation tool and motor characteristics are analyzed under different operating regimes: no-load, rated load and over load. Advantages of stepper motors are: low costs, small dimensions, possibility to transform the pulses from digital inputs into angular movement-step, number of steps is equal to the number of control pulses.

2. Hybrid stepper motor construction and principle of operation

Hybrid stepper motors have magnetic core which is excited by combination of electrical windings and permanent magnet. Images at the hybrid stepper motor is shown in Fig.1.

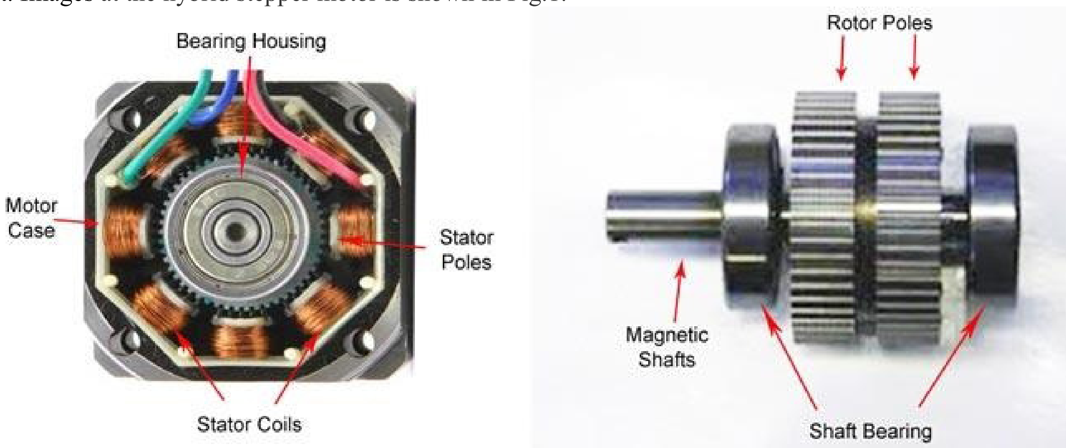

Fig. 1. Images at the hybrid stepper motor.

The hybrid stepper motor combine features of both the variable reluctance stepper and the permanent magnet stepper to produce a smaller step angle[3,5]. The rotor is a cylindrical permanent magnet, magnetized along the axis with radial soft iron teeth , shown in Fig.2. The stator coils are wound on alternating poles with corresponding teeth. There are typically two winding phases distributed between pole pairs. This winding may be center tapped for unipolar drive. The center tap is achieved by a bifilar winding, a pair of wires wound physically in paralel, but wired in series. The north-south poles of a phase swap polarity when the phase drive current is reversed. Bipolar drive is required for un-tapped windings.

Note that the 50 -teeth on one rotor section are offset by half a pitch from the other. See rotor pole detail above. This rotor tooth offset is also shown below. Due to this offset, the rotor effectively has 100 interleaved poles of opposite polarity. This offset allows for rotation in 1/100 th of a revolution steps by reversing the field polarity of one phase. Two phase windings are common as shown above and below. The stator teeth on the 8-poles correspond to the 50 -rotor teeth, except for missing teeth in the space between the poles. Thus, one poleof the rotor, say the south pole, may align with the stator in 50 distinct positions. However, the teeth of the south pole are offset from the north teeth by half a tooth. Therefore, the rotor may align with the stator in 100 distinct positions. This half tooth offset shows in the rotor pole detail above. As if this were not complicated enough, the stator main poles are divided into two phases (φ-1, φ-2). These stator phases are offset from one another by one-quarter of a tooth. This detail is only discernible on the schematic diagrams below.

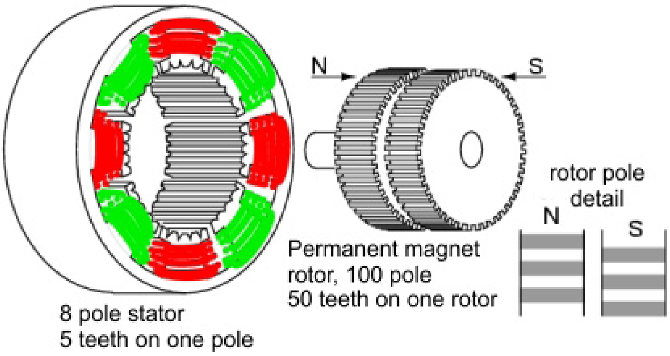

Fig. 2. Construction of hybrid stepper motor.

The result is that the rotor moves in steps of a quarter of a tooth when the phases are alternately energized. In other words, the rotor moves in 2×100=200 steps per revolution for the above stepper. The above drawing is representative of an actual hybrid stepper motor. However, we provide a simplified pictorial and schematic representation, shown in Fig.3, to illustrate details not obvious above. Note the reduced number of coils and teeth in rotor and stator for simplicity. In the next two figures, we attempt to illustrate the quarter tooth rotation produced by the two stator phases offset by a quarter tooth, and the rotor half tooth offset. The quarter tooth stator offset in conjunction with drive current timing also defines direction of rotation.

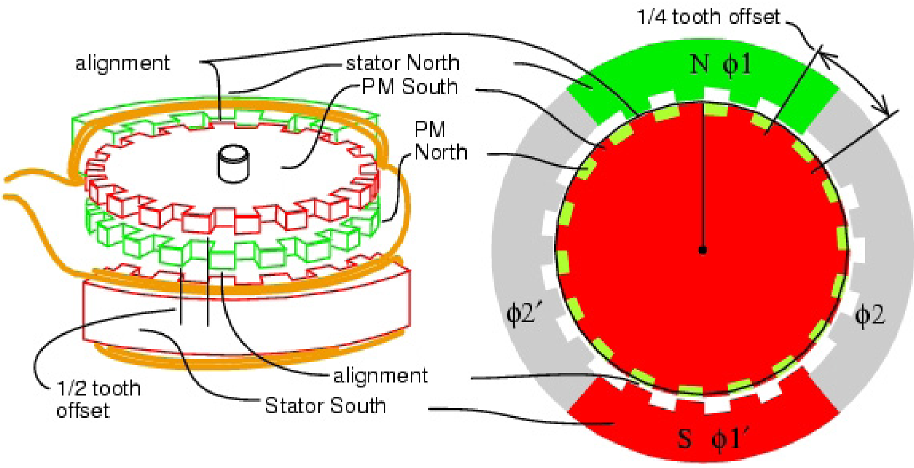

Fig. 3. Hybrid stepper motor schematic diagram.

Features of hybrid stepper schematic (Fig. 3):

- The top of the permanent magnet rotor is the south pole, the bottom north.
- The rotor north-south teeth are offset by half a tooth.
- If the φ-1 stator is temporarily energized north top, south bottom.
- The top φ-1 stator teeth align north to rotor top south teeth.
- The bottom φ-1' stator teeth align south to rotor bottom north teeth.
- Enough torque applied to the shaft to overcome the hold-in torque would move the rotor by one tooth.

- If the polarity of φ-1 were reversed, the rotor would move by one-half tooth, direction unknown. The alignment would be south stator top to north rotor bottom, north stator bottom to south rotor.
- The φ-2 stator teeth are not aligned with the rotor teeth when φ-1 is energized. In fact, the φ-2 stator teeth are offset by one-quarter tooth. This will allow for rotation by that amount if φ-1 is de-energized and φ-2 energized. Polarity of φ-1 and drive determines direction of rotation.

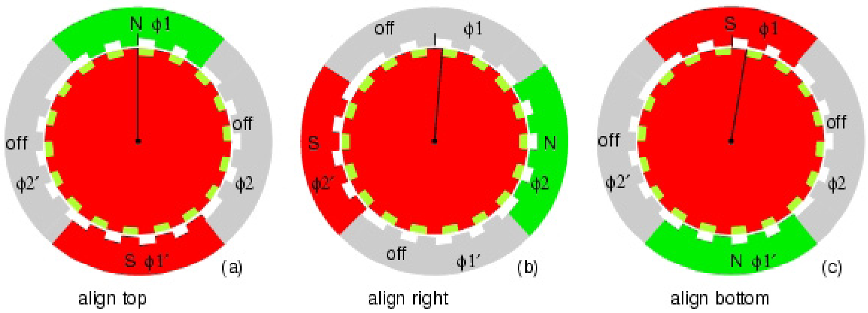

Fig. 4. Hybrid stepper motor rotation sequence.

Hybrid stepper motor rotation sequence is shown in Fig.4.

- Rotor top is permanent magnet south, bottom north. Fields φ1, φ-2 are switchable: on, off, reverse.
- (a) φ-1=on=north-top, φ-2=off. Align (top to bottom): φ-1 stator-N:rotor-top-S, φ-1' stator-S: rotor-bottom-N. Start position, rotation=0.
- (b) φ-1=off, φ-2=on. Align (right to left): φ-2 stator-N-right:rotor-top-S, φ-2' stator-S: rotor-bottom-N. Rotate 1/4 tooth, total rotation=1/4 tooth.
- (c) φ-1=reverse(on), φ-2=off. Align (bottom to top): φ-1 stator-S:rotor-bottom-N, φ-1' stator-N:rotor-top-S. Rotate 1/4 tooth from last position. Total rotation from start: 1/2 tooth.
- Not shown: φ-1=off, φ-2=reverse(on). Align (left to right): Total rotation: 3/4 tooth.
- Not shown: φ-1=on, φ-2=off (same as (a)). Align (top to bottom): Total rotation 1-tooth.

An un-powered stepper motor with detent torque is either a permanent magnet stepper or a hybrid stepper. The hybrid stepper will have a small step angle(1.8^{o}), much less than the (7.5^{o}) of permanent magnet steppers. The step angle could be a fraction of a degree, corresponding to a few hundred steps per revolution.

3. Hybrid stepper motor model

The hybrid stepper motor driver is simulated using MATLAB/Simulink`s SimPowerSystems simulation engine [18,19]. In Fig.5 is presented block diagram of stepper motor simulation model constructed of basic blocks: controller, driver and stepper motor.

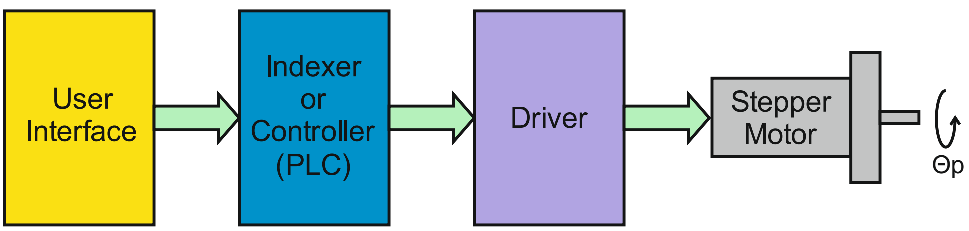

Fig .5. Block diagram of stepper motor simulation model.

Simulink model from Simulink demo library is presented in Fig. 6 and it is consisted of two section: electrical part and mechanical part [18,19]. The electrical section is represented by equivalent circuit, configuration of which depends on the motor type. The equivalent circuits have been built with the supposition that the magnetic circuit is linear (no saturation) and the mutual inductance between phases is negligible. The mechanical section is represented by state-space model based on inertia moment and viscous friction coefficient. According to Simulink model motor input parameters are: voltage per phase – V_{ph} [V] (A_+, A, B_+, B) and mechanical load torque – T_L[N·m]. Output parameters from motor model are: current per phase – I_{ph} [A], electromagnetic torque – T_e [N·m], rotor speed – w [rad/s] and rotor position – theta [degrees]. Simulink model of control circuit is shown in Fig.7.

Electrical part or motor control circuit is consisted of three functions entities: control block, hysteresis comparator and MOSFET PWM converter. The motor phases are fed by two H-bridge MOSFET PWM converters connected to a 28 V DC voltage source. The motor phase currents are independently controlled by two hysteresis-based controllers which generate the MOSFET drive signals by comparing the measured currents with their references. Square-wave current references are generated using the current amplitude and the step frequency parameters specified in the dialog window. Motor movement is controlled by two signals: STEP and DIR which are output signals from block Signal Builder. Positive value (value of “l”) of signal STEP enables motor rotation while value “0” stops the rotation. DIR signal controls the direction of motor rotation. Positive value (value of “l”) enables rotation in one direction while value of “0” reverses the direction of rotation. Converter bridges “A” and “B” are H bridges consisted of four MOSFET transistors. Bridges are supplied by 28 V DC and their outputs supply the motor windings with excitation current and enable the motor movement. Output signals from signal builder block is shown in Fig. 8.

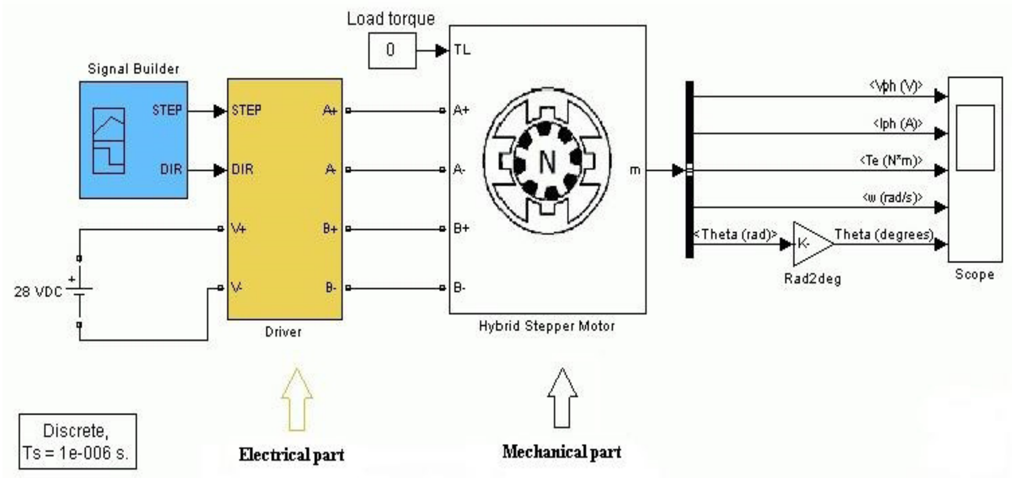

Fig. 6. Simulink model of hybrid stepper motor.

4. Simulation results

After all hybrid stepper motor parameters are input in hybrid stepper motor model simulation is run. Time for simulation execution in is defined to be 0,3 seconds according to the signals from Signal Builder block and set time in Simulink model. First simulation is run at no-load operation or stepper motor is running without any load. From the simulation results presented in Fig. 9 it can be concluded that stepper motor is moving in one direction for 0,1 seconds (STEP=1 and DIR=1), stops in period from 0,1 to 0,15 seconds (STEP=0, DIR=0), 0,05 seconds is rotating in opposite direction (STEP=1, DIR=0) and again it stops for 0,1 seconds (STEP=0, DIR=0). Hybrid stepper motor transient performance characteristics are presented in Fig.9 for no load operation.

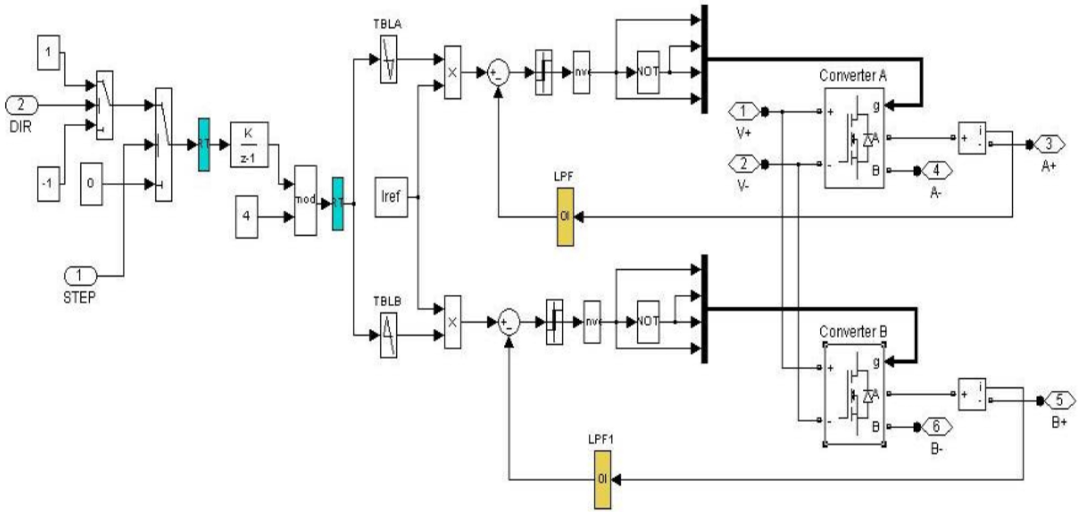

Fig. 7. Simulink model of control circuit.

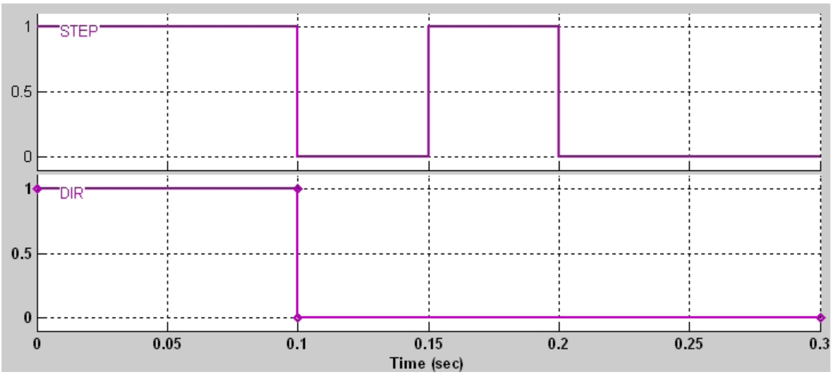

Fig. 8. Output signals from Signal Builder block.

Detailed waveforms are shown in Fig.10. With adequate zooming of presented results in Fig.9 it can be noticed that motor has reached the speed of 200 [rad/s] and have moved from position 0° to 38 degrees. It remains in that position for 0,05 seconds before it starts for time of 0,155 to move in opposite direction and it stops for time of 0,205 seconds on position 18°. For case that liad torque is increased to value of 0,1 Nm stepper motor transient characteristics are presented in Fig.11. For case that load is further increased to 0,4 Nm simulation results are presented in fig.12. Motor transient perfprmance characteristics for 150 steps/second is shovn in Fig. 13.

5. Conclusion

Different simulation software packages during recent years have proved itself as a useful tool in analyses of electro engineering problems. Simulink with its extensive block libraries enables wide possibilities for electrical machines simulation. In this paper is analyzed simulation of hybrid stepper motor transient performance characteristics under different operating regimes: no-load, rated load and overload. Simulation results proved that stepper motor is running in forward and backward direction according to the applied signals from PWM inverters to the excitation windings and only in case when applied load is smaller than motor electromagnetic torque. In case when external load is bigger than stepper motor electromagnetic torque no rotor movement is achieved and stepper motor speed is rapidly going to zero very shortly after motor start.

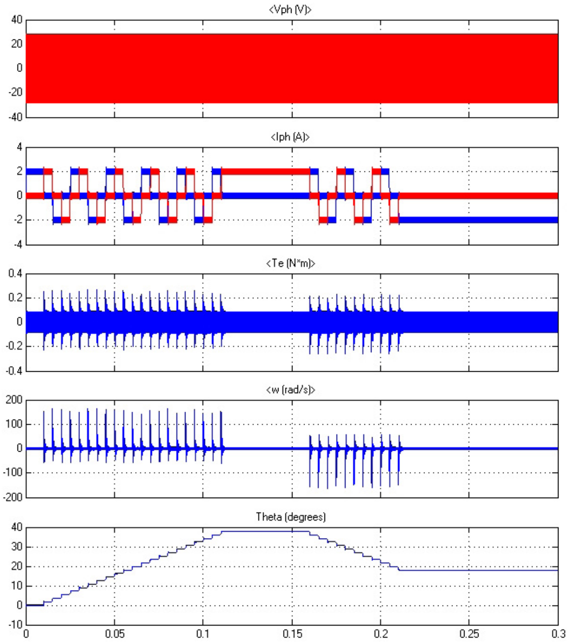

Fig.9. Hybrid stepper motor transient performance characteristics at no-load.

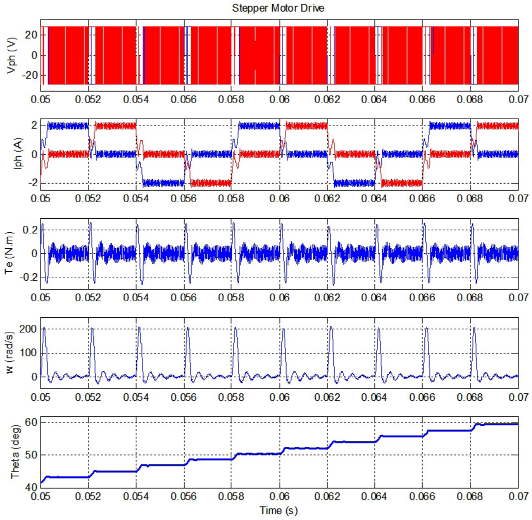

Fig. 10. Detailed waveforms

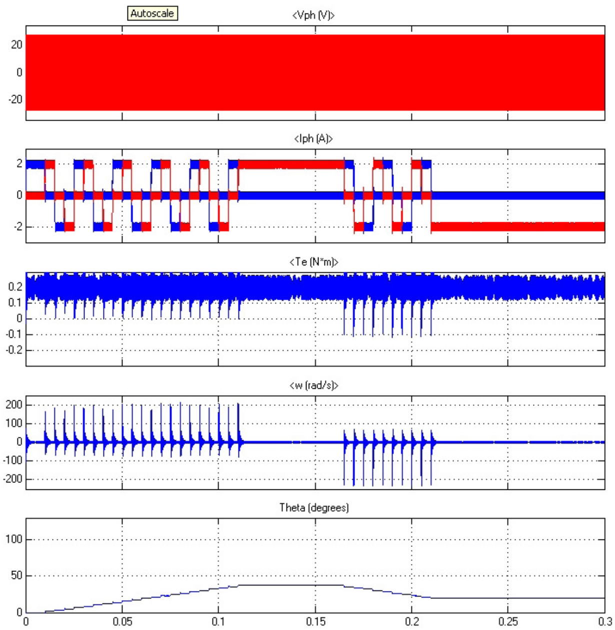

Fig. 11. Hybrid stepper motor transient performance characteristics for load 0.1 Nm..

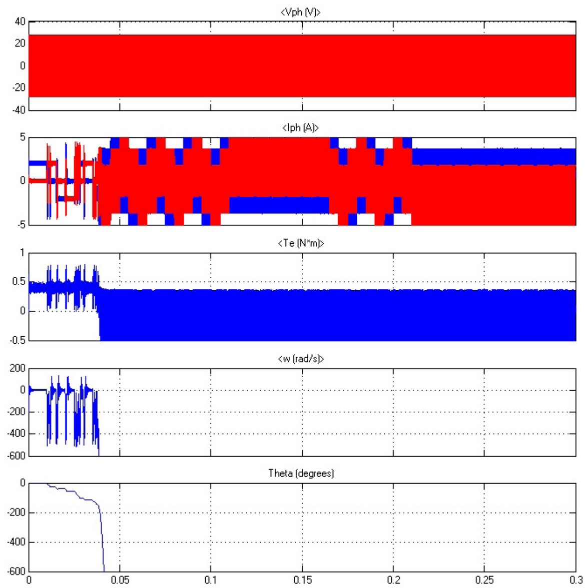

Fig. 12. Hybrid stepper motor transient performance characteristics for overload of 0.4 Nm.

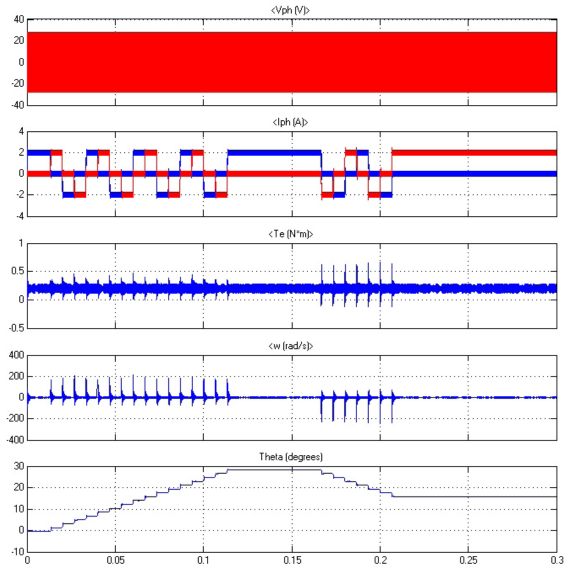

Fig.13. Hybrid stepper motor transient performance characteristics for 150 steps/second.

All the obtained results for diverse regimes are in good accordance with the theoretical expectations and also with the results of analytical computations. Application of simulation packages has considerably improved electrical machines analysis replacing the expensive laboratory equipment and enabling performing of different experiments easy and with no cost.

Acknowledgements

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